Indian J. Phys. **74B (2)**, 101–115 (2000)

I J P B
— an international journal

Attenuation by rain and associated radio propagation at microwave and millimetrewave frequency bands for communication

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Received 23 September 1998, accepted 11 January 2000

Abstract : The present state of knowledge on the distribution of rain characteristics including 0°C isotherm height is critically reviewed Emphasis is also laid on the rain dropsize distribution, exceedance of thresholds, probability of exceedance, scattering patterns, *etc*. The physics of rain attenuation and the associated characteristics are discussed at lengths In addition, rain fades and depolarization involved, have been thoroughly examined. Attenuations along slant path including the propagation mechanisms are considered. Finally, scopes of future investigation/research are outlined.

Keywords : Rain attenuation, 0°C isotherm height, depolarization

PACS No. : 94.10.–s

Plan of the Article

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1. Introduction

The performances of microwave and millimetrewave communication links and radar propagation are degraded by different hydrometeors such as rain, hails, snow, fog, *etc*. Among all these hydrometeors rain is the most important parameter which imposes serious limitation on such links.

The system performance of terrestrial or earth-space link operating at frequencies above 10 GHz is severely degraded due to the presence of rain along the propagation path. The path-averaged attenuations in rainfall as measured by radar and radiometer operating at 13.8 GHz have been compared by Durden *et al* [1]. Microwaves with frequencies less than 10 GHz have wavelengths much larger than the size of the raindrop, and thus are not affected by rains. On the other hand, the wavelength approaches the dimension of dropsize as the frequency increases. Rain, because of its high dielectric constant, produces heavy displacement current.

As a result, the Ohmic losses in the rain drop at frequencies higher than 10 GHz produce significant attenuation [2,3]. Therefore, rainfall statistics over an area are very necessary for a system design. The percentage time during which absorptions are significant are estimated from these rain statistics and thereby the rain-induced outage time is derived. An extensive account of rainfall statistics, its types, variability and parametrizations, considering a wide range of global rain zone, has been provided by Moupfouma [4] towards the development of rain rate distribution models for radio system designing. Information regarding time variant fading is also important. That means if we know the duration of fading, then a decision can be made to take action or wait for the signal to recover. Therefore, fade dynamics, fade duration, *etc.* are the subjects which are being looked into closely. Naturally it relates to the subject of rainfall rates. The attenuation due to rain can be better estimated if the rain characteristics, such as rain rate, its distribution, exceedance of thresholds, probability of exceedance with reference to the total rainfall time, dropsize, extension of rain cell (equivalent paths length), 0°C isotherm height, *etc.* are known.

Specific attenuation, $\alpha(R)$, depends on rain rate (R) through the relation [5]

$$\alpha(R) = a\,R^{b}, \qquad (1)$$

where a and b are constants. Again R depends on rain drop diameter (D) and number density $N(D)$ through the relation [6]

$$R = 6\pi \cdot 10^{-4}\int^{\infty} V \cdot D^{3} \cdot N(D)dD. \qquad (2)$$

The total attenuation is the product of specific attenuation and effective path length [7]. In case of earth-space path, the effective path length is considered to be the rain height. The rain height is taken as 0°C isotherm height.

For the dependable planning of microwave and millimetrewave links, it is essential to have the statistical distribution of rain attenuation. Again, to obtain long term rain attenuation, statistics of many years of recording is necessary. Rain rate measurements for a number of years are available from many countries. Models that can predict rain attenuations from such rain statistics have been proposed by many workers since long [8,9]. On the basis of the concept of moving rain cells with limited extension, a new model was developed by Hansson [10] in predicting rain attenuation from rain rate statistics. Prasad *et al* [11] have compared some of the above attenuation prediction models with the attenuation observed by radiometers operating at 11 GHz with an elevation angle 10° over Delhi and at 13.4 GHz along the vertical paths over Delhi (28.6° N), Ranchi (23.3° N) and Gulmarg (34.1° N). While Garcia–Lopez's method shows an excellent agreement with the observed values, the Moupfouma's method underestimates them. A brief review of hydrometeor scatter interferences, highlighting recent improvement of CCIR texts on interference between terrestrial and earth-space links has been made by Olsen *et al* [12]. Some directions such as (i) improved horizontal structure model for precipitation, (ii) improved rain height model (iii) inclusion of melting layer scatter, (iv) reflectivity factor slope above the rain height, *etc* have also been suggested by them for possible future investigations/research.

In the present paper, a brief survey is made as to the effects of rain characteristics and related parameters on microwave and millimetrewave communication link as observed by different workers, and has been viewed with reference to the measurements made over some Indian tropical stations.

2. Distribution of rain rate

Rain rate and its associated parameters such as duration exceedance of rain rate, *etc* are important for the estimation of attenuation. The detailed accounts of rainfall rate and duration statistics for microwave system design have been provided by Villar *et al* [13] and Watson [14]. The duration of exceedances of different rain rates has, of late, become the topic of studies [15]. Similar statistics and the duration of exceedance of different rain rates (thresholds) as well as the exceedance probability with reference to the yearly total rainfall time over two tropical Indian stations (Calcutta and Delhi) have been provided by Mondal *et al* [16–18]. According to the CCIR (ITU-R, 1990) classification [19] the two tropical stations Delhi and Calcutta fall within the K-type and N-type climate zones, respectively. The year to year variations in rain rate distribution over the coastal station Calcutta are not substantial, whereas for Delhi the year-to-year variability is quite significant. The CCIR (ITU-R) values are found to correspond more closely with Calcutta values rather than those for Delhi. The average distributions show that at 10^{-2}% probability level the average rain rate over Calcutta is ~85 mm/h, whereas that over Delhi is ~65 mm/h. It may be mentioned that systematic measurements of both rain rate, using fast response rain-gange, and microwave propagation around 13 GHz for LOS over terrestrial as well as slant paths, were made by Calla *et al* [20] over six climate regions in India and their results indicated that unlike CCIR report about Indian climatic zone, the Indian subcontiment may be subdivided into nine distinct rain regions.

The parameters R, D and T_1 (where R is the rain rate, D the duration of exceedance of a particular rain rate and T_1 the total time of a propagation experiment in hrs or in min) are necessary for the rain rate data analysis. The total time/duration (D) of exceedance of a particular rain rate (R) may then be represented as the percentage (P) of total time (T_1) of records, *i.e.*, $P = D \times 100/T_1$. Therefore, as pointed out by Villar *et al* [13] and Moupfouma [14], the study of duration of exceedance of different rain rate is as important as that of magnitude and probability of occurrence of fade for the propagation studies. The probability of exceedance may be termed as the fractional number of exceedance (P_n) with reference to the total rainfall time per year and is defined as $P_n = \overline{N}/\overline{D}$,

where $\overline{N}$ = Av. number of times per year that a particular threshold is exceeded,

$\overline{D}$ = Av. total rainfall time per year.

Similarly, P_d is defined as

$$P_d = D/\overline{D},$$

where D is the total duration of a particular rain exceedance.

When a rain rate exceeds a particular value it is called an exceedance. The particular value that is exceeded is then known as threshold. Each exceedance has an associated duration (D). The probability of exceedance of threshold (P_n) and that of duration of exceedance (P_d), during total rainfall time, as a functions of thresholds are shown [17] in Figures 1 and 2. Moreover, the duration of precipitation rate, particularly of high intensity, is of immense importance for estimating the fadeout period and, consequently, for taking corrective measures for microwave communication system.

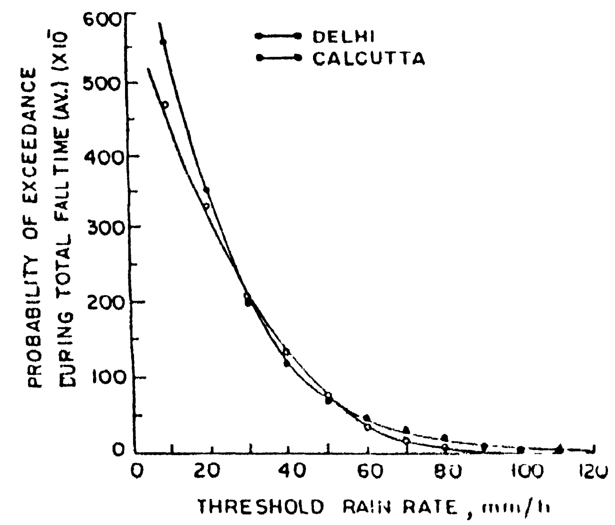

Figure 1. Probability of exceedances of threshold as a function of threshold.

The duration of rain rate is found to vary substantially from year to year over Delhi, while over Calcutta, except for the rate less than 40 mm/h in the year 1985, the duration of any rain rate remained almost the same. The yearwise variation of rain rate duration becomes insignificant over both Delhi and Calcutta as one proceeds towards higher rain intensity (50 mm/h and above). Year-to-year wide variability in the number of events is also observed over Delhi, while over Calcutta such variation is not there at all except for the year 1985 when a deviation is observed for lower rate of precipitation.

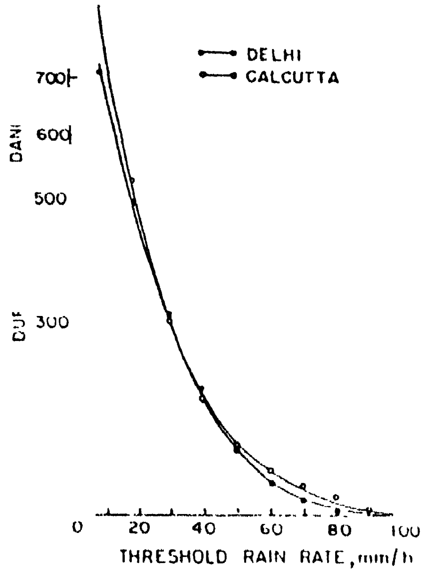

Figure 2. Probability of duration of exceedances as a function of threshold

The rain rate distributions over several other stations in India, on the basis of heavy rainfall data recorded by IMD using rain gauges with 15 min integration time and those recorded by rapid response rain gauges having integration time 10 s, show substantial difference between rain rate at each individual stations [21].

According to heavy rainfall data, the rain rates for all months over Calcutta is found to be ~85 mm/h at 0.01% probability level, while those for Bombay (a south-western station) and Shillong (a north-eastern hilly station) are ~80 mm/h and ~68 mm/h, respectively. But, when measured by rapid response rain gauge, the corresponding values are found to be ~122 mm/h, ~130 mm/h and ~130 mm/h for Calcutta, Bombay and Shillong, respectively, which are much higher and are comparable with each other for these stations.

The relationship between two rain rates having different integration times is given by power law [5]

$$R_t = a\,R_T^b, \tag{3}$$

where R is the rain rate in mm/h, t is the integration time at which the rain rate is required, T is the integration time at which rain is available, and a and b are constants depending mainly on frequency of propagation.

Using rain data collected at Delhi by rain gauges with 10 s and 15 min integration times, Sarkar *et al* [21] obtained the power law which is as follows :

$$R_{10\,s} = 2.567\,R_{15\,\text{min}}^{0.852} \tag{4}$$

Using data collected by Ajayi and Ofoche [22] at Ile-Ife (7.5° N, 4.5° E), a tropical station in Nigeria, the power law was obtained for 10 s and 10 min integration times as

$$R_{10\,s} = 2.076\, R_{10\,min}^{1.011}. \tag{5}$$

Flavin [23], using rain rates obtained by rain gauges with integration times 1 min and 6 min for different stations in Europe, USA, Canada and Australia, obtained the relationship as

$$R_{1\,min} = 0.0990\, R_{6\,min}^{1.054}. \tag{6}$$

From the above relations, it is found that the values of b for temperate and tropical stations are comparable with each other and have a good agreement. But the values of a for temperate and tropical locations do not agree with each other. This may be due to the dominance of convective rain in tropics and wide spread (stratiform) rains in temperate zones.

Goldhirsh and Gebo [24] investigated the rain rate distribution and slant path attenuation (at K_a band) for a mid-Atlantic coast region of USA. The rain gauges used in the network for the measurement of rain were of tipping bucket type. They considered 10 sites. Rain rates for these sites were calculated for the one-year periods 1986–87 and 1987–88, and for a two-year period 1986–88. A previous 6 years (1977–83) temporal average was also calculated for a particular site. The distribution of rain for the year 1987–88 was found to be smaller than that of 1986–87, suggesting that significant non-rainfall periods existed during 1987–88. But when the network average rainfall for two-year period 1986–88 was compared with 6 years temporal average of a single site, it was found that they coincide with each other. The fact suggested the non-variability of rain rate over an extended period. That means, the spatial averaging of the individual rainfall distribution over a short time period might be equivalent to the averaging of the rainfall at a particular site for a longer period.

A rain gauge having 1–2 min time resolution resolves the small but significant cells. Gauges having larger times would miss the peaks of the rain cells. It was found that 0.1–1% of year interval, the distribution function for hourly observation gives a good estimate of 1 minute-averaged rain rate (distribution).

Surface point rain rate :

There is no strong physical theory so far for the calculation of distribution of surface point rain rate. Thus the estimate of rain rate distribution is empirical and has to be developed using a long term observation of rain accumulation. There exists two types of accumulation data, (i) the hourly daily and annual accumulation for longer duration that are available for a large number of geographical locations and (ii) excessive rainfall data from limited number of locations. The instantaneous rain rate data are available for a very limited number of locations or for a limited duration. More than 10 years of observations are necessary at a point for estimation of surface rain rate to exceed 0.001% of year on an average. The uncertainty in this respect is less than 10% of the estimated value.

Advanced Commun Technology Satellite (ACTS) :

On the basis of ACTS propagation experiment, Crane and Robinson [25] studied rain rate characteristics over several sites in USA, and a detailed comparative study of three models, namely (i) Rice-Holmberg model, (ii) ITU-R rain climate zone model and (iii) Crane-Global rain climate-zone model, has been provided. The results of predictions from these models were taken into consideration to illustrate the difference in the expected rain-rate distribution recommended by ITU-R [26].

A mathematical model for estimating the probability distributions of rainfall rate from the base line data of 30 years mean annual rainfall and total number rainy days (rain fall greater than 0.3 mm/h) has been developed recently by Timothy and Sarkar [27] and is given as follows :

$$P(R) = \alpha \cdot \exp(-\beta R) \tag{7}$$

where, $P(R)$ is the percent of time that a specified amount of rain rate occurred in a year, R is the rain rate and α and β are the parameters that depend on mean total rainfall M, and number of rainy days D. The parameter M is given as

$$M = -\frac{87.60}{(60\times 60/\tau)} \times \frac{D}{365} \times \frac{\alpha}{\beta} \times (e_1 - e_2), \tag{8}$$

where τ = Integration time;

$$e_1 = \exp(-\beta R_{max}) \times \left(R_{max} + \frac{1}{\beta}\right);$$

$$e_2 = \exp(-\beta R_{min}) \times \left(R_{min} + \frac{1}{\beta}\right),$$

R_{max} and R_{min} being the maximum and minimum rain rate, respectively. It was assumed that $P(R)$, occurred in a year follows R exponentially. When $P(R)$ decays by half of its initial value,

$$\beta = 0.693 / R_c,$$

where R_c is the rain rate at initial value of $P(R)$. The value of α is then obtained by substituting β in eq. (7) with suitable values of R_{max}, R_{min} and R_c. The values of R_{max} and R_{min} are taken to be equal to 250 and 0 for this model (as the maximum rain rate over India is found to be 250 mm/h). The rain rate value that exceeded maximum percentage of time in a year (R_c) was found to lie between 0 and 20 mm/h over many Indiian stations. Thus, having known the value of α, the modelled probability distribution of rain rate as expressed by eq. (7) can be determined.

The results obtained from this model are found to be in good agreement with measured values. The assumption of exponential distribution of the percentage of time that a specified rain rate occurred in a year is found to be a good approximation for the tropical Indian stations.

3. 0°C isotherm height and its distribution

In order to estimate rain attenuation, two important parameters are considered : one is the rain rate discussed in previous section and the other is rain height. According to a number of studies conducted by many workers [28], it is now well established that 0°C isotherm height is close to rain height. These 0°C isotherm heights are derived from upper air measurements.

Rain is characterised by a constant reflectivity (of radiowave) from surface to the 0°C isotherm height [29]. It is worth mentioning that constant reflectivity implies the constancy of specific attenuation in the vertical structure. Thus, for the prediction of vertical attenuation, the height of 0°C isotherm, being an important parameter, plays an important role. The height of 0°C isotherm depends on different meteorological conditions. It is found that the average height of 0°C isotherm varies from 4.7 km in the tropics to 3.1 km at latitude 40–60°. A high correlation between average 0°C isotherm height and the height at which raindrops exist, should not be expected for the higher rain rates. This is because large water droplets may be carried aloft above the 0°C isotherm height in the strong updraft cores of intense rain cells. Even large drops can be observed up to a height corresponding to the temperature near –5°C. Observations on effective rain height have also been reported by Portes *et al* [30].

Matricciani [31] reported the performance of his earlier two layer rain model [32] at three equatorial sites in Brazil against the radiometric data of attenuation at 12 GHz collected for two years. The later test report [31] shows that the two layer rain model predicts probability distribution very well in the above three low latitudes locations (equatorial areas). This is in contrast with Crane's observation that in the equatorial region, significant modelling errors exist for all models [33]. The two-layer rain model is based on radiometric measurements and physical hypotheses of Pontes *et al* [34]. The model assumes the rain height (*i.e.*, height of 0°C isotherm) to be 4 km for latitude 36° and 4–0.075 (ϕ – 36) km for latitude (ϕ) above 36° as given by CCIR, 1988 [35]. But according to the CCIR report [36], the rain height has been changed to 5 km for latitude 23° and 5–0.075 (ϕ – 23°) km for latitude (ϕ) above 23°. However, the rain height obtained for temperate climates, following the reports of CCIR, is found to be the same. The results also suggest that the rain height according to the CCIR report is too high for latitude around 23° and the equatorial rain zones are too coarse that needs further subdivision for rain attenuation prediction.

Sarkar *et al* [37] and Mondal *et al* [38] have provided results on 0°C isotherm height over some selected Indian stations. The distributions of 0°C isotherm height over different stations were discussed in the light of prevailing weather characteristics over the stations. The 0°C isotherm height varies in different seasons, namely, winter, summer (premonsoon), monsoon and post-monsoon, due to the climatic variation. Over Bangalore (12°58′ N, 77°35′ E), there is not much variation of rain height (0°C isotherm height) during different seasons. It varies from 4.5 km to 6 km in all seasons. This is due to the fact that there is not much variation of meteorological parameters like temperature, humidity, *etc.* over Bangalore. However, over Calcutta (22°39′ N, 88°27′ E) and Delhi (28°35′ N, 77°12′ E), the variations of 0°C isotherm height are quite appreciable during different seasons. Over Calcutta, in monsoon months, 0°C isotherm height varies between 5 km and 6 km; between 4 km and 5 km during pre-monsoon; and between 3.2 km and 4.8 km during winter The summer and winter over Delhi are well defined. The variation of 0°C isotherm height in winter has been found to range between 2 km and 4.2 km. During pre-monsoon months, the variation of 0°C isotherm height is not that appreciable while during monsoon and winter months it is quite significant.

Figures 3–6 show the distribution of 0°C isotherm height during different seasons over Trivandrum (08°29′ N, 76°57′ E), Bombay (19°07′ N, 72°51′ E), Gauhati (26°05′ N, 91°43′ E) and Lucknow (26°45′ N, 80°53′ E), respectively.

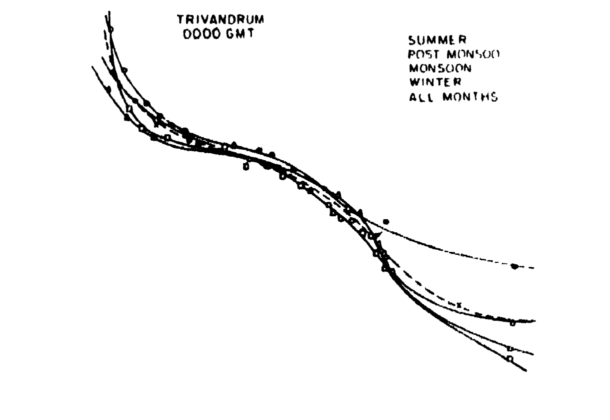

Figure 3. Probability distribution of 0°C isotherm height during different seasons over Trivandrum.

The effect of ground temperature on rain height as observed by Sarkar *et al* [37] is shown in Figure 7. The correlation between these two parameters was observed to be poor, if the data points of all seasons and times are taken together. However, several regression lines can be drawn in different seasons and times. The ground temperature varies from 11°C to 24°C, while 0°C isotherm height varies from 3.3 km to 5 km during 0000 hrs GMT in winter. From Figure 7 it is clear that 0°C isotherm height increases as the ground temperature increses in various seasons and times.

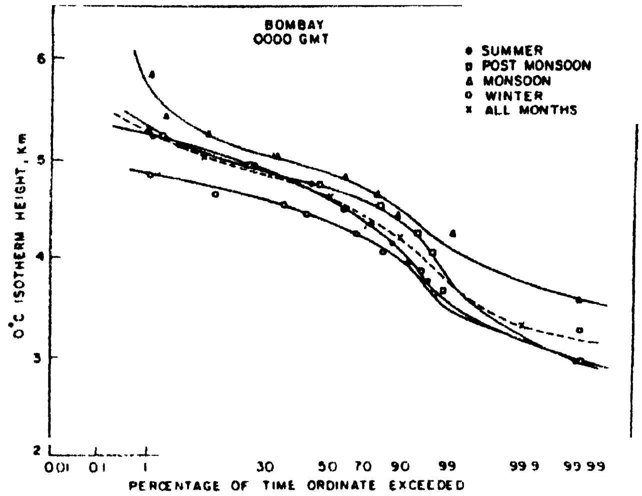

Figure 4. Probability distribution of 0°C isotherm height during different seasons over Bombay.

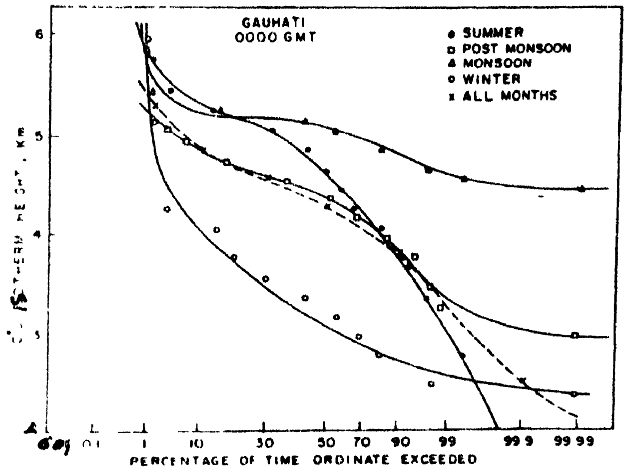

Figure 5. Probability distribution of 0°C isotherm height during different

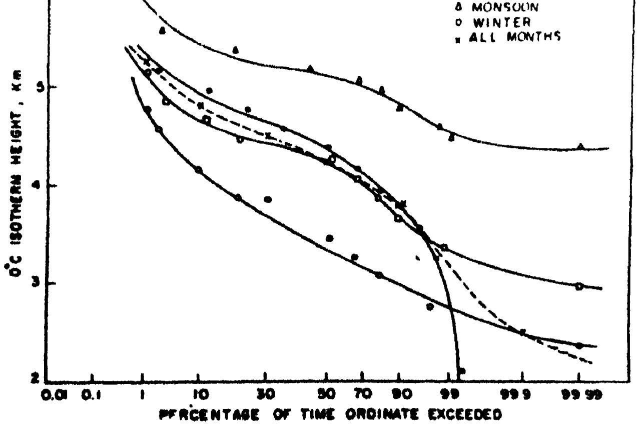

Figure 6. Probability distribution of 0°C isotherm height during different seasons over Lucknow.

Sarkar *et al* [37] also estimated the 0°C isotherm height using different theoretical models, which are developed on the basis of temperate climatic condition. The 0°C isotherm

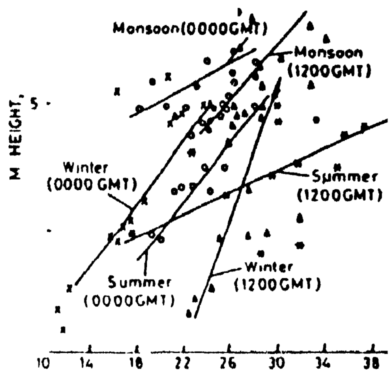

Figure 7. Effect of ground temperature on 0°C isotherm height during different seasons and times.

height pertaining to winter months, that too, over some selected stations were found to agree with the values derived from these theoretical methods. However, at station like Bangalore, whose latitude is 12.58°, the observed values do not agree at all with the theoretical values derived. Similarly, the values observed over Delhi, Calcutta and other stations in monsoon, pre-monsoon and post monsoon, also do not agree with the theoretical values. Therefore, the theoretical methods as developed by different workers [28] on the basis of temperate climate condition cannot be used over Indian tropical latitudes. However, according to the CCIR recommendation *Rec. ITU-R PN 839*, 1994, it is important to mention here that the *Rec ITU-R PN 839* may be used for the estimation of 0°C isotherm height only for monsoon period over Indian stations. But it is not valid for other seasons. Similarly the CCIR recommendation *Rec. ITU-R PN 618-2*, 1992, is found to be applicable for the estimation of effective rain height only in winter months over Indian tropical stations.

Another interesting feature observed by Sarkar *et al* [37] is that the rainfall occurs due to thunder storms and low clouds in Indian tropic. The rainfall due to thunder storms occurs from far above the 0°C isotherm height ranging between 10 km and 12 km. Rainfall from such height is associated with supercooled rain drops. Rainfall from clouds lying well below the 0°C isotherm height (known as warm rains) are quite common in tropical station, particularly, in north-eastern region of India. All these observations suggest that there is complexity towards the determination of effective rain height due to typical characteristics of rainfall over Indian latitudes. The distribution of 0°C isotherm height over different station and seasons also indicates that 0°C isotherm height strongly depends on latitude and local weather characteristics.

4. Rain dropsize distribution

The attenuation of microwave and millimetrewave also depends on the rain dropsize distribution. Quite a good number of models on dropsize distribution have been employed for evaluation of the effects of microwave and millimetrewave propagation due to rainfall. Models of Laws and Parsons [39], Marshall and Palmer [40], *etc.* on the dropsize are widely used for the estimation of rain attenuation. But the above two models have been shown to be inedequate for the dropsize distribution studies for tropical station Ile-Ife in south-western Nigeria [41]. The specific attenuation is related to the rain rate through rain dropsize distribution. The specific attenuation can be estimated from the following power-law relation given by Olsen *et al* [5]

$$\alpha(R) = a\,R^{b}, \tag{9}$$

where $\alpha(R)$ = Specific attenuation at rain rate R,

R = Rain rate, and a and b are constants depending on frequencies.

Using the above relation and assuming the shape of drops spherical, the values of a and b were calculated by Olsen *et al* [5] for different drop temperatures and dropsize distributions at different frequencies in the range 1–100 GHz. A relation between the rain rate and the number density was given by Fang and Chen [6] as follows :

$$R = 6\pi \cdot 10^{-4}\int VD^{3}\cdot N(D)\cdot dD, \tag{10}$$

where R = Rain rate (mm/h),

V = Terminal velocity,

$N(D)$ = Number density, *i.e.*, number of drops per diameter interval per m^3,

D = Drop diameter (mm).

This exponential distributions are found to be valid only for a specific range of drop diameters depending on the measurement technique. The log-normal distribution has the form

$$N(D) = \frac{N_T}{D\sqrt{2\pi}\ln\sigma}\cdot\exp\left[-\left\{0.5\,\frac{\ln(D)/D_m}{\ln\sigma}\right.\right] \tag{11}$$

where $N(D)$ = Number density,

N_T = Total number of drops of all sizes,

D = Drop diameter,

D_m = Geometric mean diameter of rain drops,

σ = Standard deviation.

For meteorological studies, the distinction between exponential and log-normal distributions is not significant. Both these approximations fit the measurement results equally well for drop diameters greater than or equal to 1 mm. The exponential distributions are preferred because of simplicity. However, an accurate account for raindrops with small diameters is as important as for large drops Depiction as to how drop radius and frequency act in the variation of specific attenuation has been made by Watson [42].

A new technique for inferring path averaged rain dropsize distribution from measurements of infrared attenuation and rainfall rates along the path has been provided by Maitra and Gibbins [43]. Jassal *et al* [44] did their experimentation at Dehradun in northern part of India, using a disdrometer This instrument is capable of differentiating rain drops of about 1 ms time gap. The details of the disdrometer, its operation and working have also been described therein. The data collected by disdrometer were analysed for rain rate with 1 min integration time. The maximum rain rate with 1 min integration time was found to be 120 mm/h. The rain dropsize data were collected for a period of 4200 min during monsoon of the year 1992. From these data, the rain rate as well as dropsize distribution for each rate were calculated The data were used mainly to study the dropsize distribution and not to derive cumulative rain statistics. As the CCIR data are based on the collection from temperate zones, the rain dropsize distribution adopted presently by CCIR is not very accurate, because it ignores the number of small rain drop which are significant at the shorter mm-wavelength. The number of rain drops per unit volume per unit diameter interval was calculated for a rain rate of 49.6 mm/h at Dehradun. The values thus obtained were compared with those of Nigeria, having the same rain rate.

Log-normal distribution of rain dropsize have been reported from countries like Nigeria [45], Brazil [46]. The log-normal distribution of dropsize as a function of number density of drops per diameter interval shows profiles of parabolic shape for both highest and lowest rain (146 mm/h and 0.23 mm/h, respectively) [41]. The model developed by Verma and Jha [47] is also found to follow log-normal distribution for tropical climate. Figure 8 shows a comparision of log-normal distribution of rain dropsize as

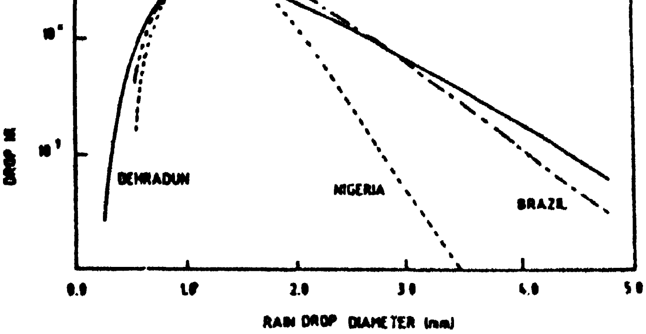

Figure 8. Comparison of log-normal RDSD models at 80 mm/h rain rate.

obtained from Dehradun, Nigeria and Brazil for a rain rate 80 mm/h. Verma and Jha [48] developed a specific attenuation model based on the rain dropsize data collected by disdrometer at Dehradun in India for various frequencies ranging from 36 GHz to 100 GHz. Smaller drops are found to be responsible for higher attenuation at ~100 GHz for a rain rate below 30 mm/h. Figure 9 shows a comparison of proposed model of specific attenuation with other models for different frequencies.

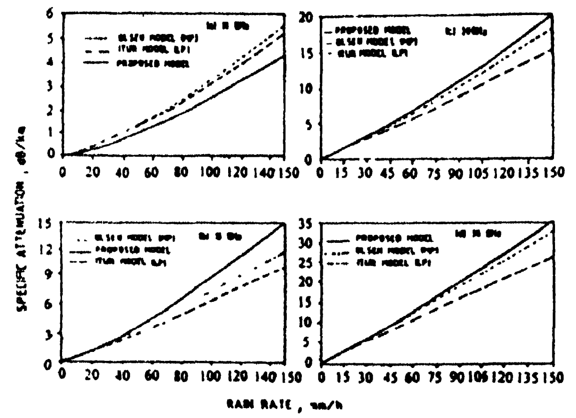

Figure 9. Comparison of proposed model with existing models (a) 10 GHz, (b) 15 GHz, (c) 20 GHz and (d) 30 GHz; M P-Marshall and Palmer [40]; L P-Laws and Parsons [39].

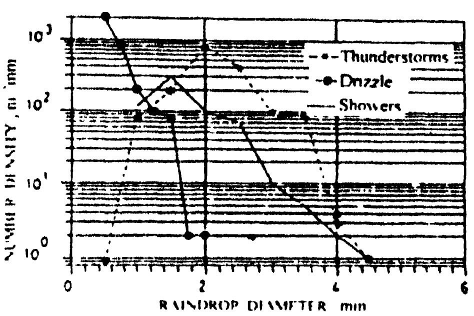

Figure 10. Rain dropsize distribution (RSD) over Gauhati.

Figure 10 shows the rain dropsize distribution over Gauhati, India, which displays variation in pattern with rainfall type [49]. For thunderstorm shower, it follows a log-normal pattern, whereas for drizzle, it can be represented by the negative exponential model. The values of coefficient a and b in the relation $\alpha(R) = aR^b$, therefore, strongly depend on the rainfall type. The study indicates that attenuation for frequencies less than 30 GHz must be dealt seperately for various types of rainfall. But this type of discrimination may not be necessary for frequencies ~30 GHz.

Dual polarization radar technique has been extensively examined for the improved estimates of rainfall characteristics by many workers [50,51]. It is observed that the rain drop radar cross-sections are proportional to the sixth power of drop diameter, while rain attenuation at mm-wavelength is sensitive to the number density of smaller drops and it increases as the density increases [42]. Thus, the accuracy in prediction of mm-wave attenuation depends on the dropsize distribution.

If results from one climatic region need to be scaled for other regions or if the predictions based on rainfall rate are to be relied upon, an extensive study of the variations of dropsize distribution is required. Investigations are on, and the results from different regions of the world, employing different frequencies in the microwave range, have been brought into focus by differnt researchers [52–54]. Calla *et al* [55] conducted some measurements on rain dropsize distribution at Ahmedabad using a ground based spectrometer. But, reliable model has not been established so far for Indian region which has a wide range of climatic conditions for different zones. The ITU-R prediction models are mainly based on the data of temperate zones. The rain rates of these temeprate zones are low. Moreover, the dropsize distributions are varying. Thus, these ITU-R models were found to be insufficient for tropical zone like India where heavy rainfall occurs.

5. Scattering

The scattering and absorption cross-section of water drops are of the same order, indicating that the signal extinction is due to both scattering and absorption. The coherent scattering model is used for the calculation of rain attenuation in the microwave and lower millimetrewave range. The effect of incoherent scattering on attenuation and depolarization of millimetrewave due to hydrometeors have been studied by Oguchi [56]. Calculations done by Oguchi [56] suggest that the incoherent terms in the forward scatter can be neglected for radio links up to at least ~200 GHz. At a rain rate of ~2.5 mm/h for a 5 km propagation path pulses of 100 GHz show that the major part of pulse has transmitted unchanged but followed by small amplitude. With rain rate of ~25 mm/h, distortion was significant with the pulse spread over ~7 s. However, in the latter case, the attenuation was 60 dB. At 90 GHz, for example, a 1-km thick region of cloud with ~1 gm/m^3 of liquid water will contribute ~5 dB attenuation, whereas an equivalent thickness of rain at ~12.5 mm/h, intensity would contribute only ~3 dB. Prediction techniques including a mixture of water vapour, cloud melting zone and light rain effects are the subjects of current study. Ice clouds make little contribution to attenuation below about 60 GHz, but above 100 GHz their contribution is significant and comparable to that resulting from water drops of the same size distribution.

Results on rain attenuation at 94 GHz on a horizontal path length of ~312 m on using vertical polarization were reported by Gloaguen and Lavergnat [57]. The observation at 94 GHz (= 3.2 mm, which is of the order of the rain drop-size) was aimed at the question whether multiple scattering affects the propagation or not and also to test the classical expression for specific attenuation which is estimated from the product of extinction cross-section of the scatter by their size distribution. The first order multiple scattering provided to be sufficient enough to describe the coherent attenuation at this frequency. The different techniques adopted by ITU-R for coordination contour calculation of hydrometeor-scatter interference are detailed by Olsen *et al* [12]. Thurai and Goddard [58] suggested that melting layer scatter should be taken into account in calculating both the coordination-contour and detailed-interference for frequencies in and below 11–14 GHz band. The effect appears to be greatest for 4–6 GHz band, but even at 11 GHz, the interference enhancement exceeds that incurred in moving from one "interference rain climate" to the next intense one.

6. Rain attenuation

The propagation phenomenon in the centimetre and millimetrewave bands and attenuation due to rain have been the subjects of research for tropospheric communication links since long. Presently, the emphasis is laid on establishing prediction techniques for the estimation of attenuation for a particular propagation path. For estimating the path attenuation, meteorological data are very important. The complex nature of rain structure, its regional variabilities and the difficulty for measuring high rate of rainfall have made the task hard enough to establish a relationship between different variables. Spatial and temporal distribution of rainfall as well as the total amount of rainfall are poorly known and has been the objectives of research by different international bodies including ITU-R. The point rainfall rates and the vertical and horizontal structures of rain are of immense importance for estimating rain attenuation. Over the last several years, many models have been proposed and extensive research activities have been conducted to improve the already existing prediction models. Fedi [59] outlined some desirable features for prediction model. According to him (i) the model should be checked against directly observed physical data, (ii) it should be tested against measured data from different region and (iii) it should be simple and structured to accept modification. Therefore, a need is always felt by the radio community to refine the existing propagation models taking into account the local radio meteorological parameters. Rogers [60] developed a rain storm model from weather radar data for conversion of rainfall statistics to path attenuation. From a comparison of radar based attenuation and measurements of simultaneous path, Goldhirsh [61] indicated that the rain below the bright band is responsible for attenuation. The bright band, the so called melting layer, was thought to be due to the melting of ice and available as large water coated snow particles which might produce significant attenuation. Crane [62] from linearly polarized radar measurements of change in cross-section, concluded that the melting of ice mainly takes place below the bright band (as the bright band itself is dominated by snow) and this significant melting occurs at a height near 0°C isotherm. The process of melting goes on and produces minute droplets at the extremities of show flakes. This grows bigger and finally becomes rain drop. The attenuation was found to be propotional to the melted water till it becomes the rain drops. The view that the melted rain drops produce significant attenuation was supported by the observation made by Goldhirsh [61].

6.1. *Characteristics of rain attenuation :*

In relation to different rain parameters, the propagation characteristics have been examined by many workers [3,4]. Crane [63] described statistical uncertainty in attenuation prediction (including that of rainfall) and provided a procedure to estimate the risk associated with that prediction of earth-satellite link.

The diurnal variation of rain attenuation at 11.2 GHz on a satellite path in Indonesia over a three-year period was reported by De Maagt *et al* [64]. The Ku-band services were found to suffer more in the late afternoon and evening hours during wet months, because the incidence of thunder storm activity and rainfall occur in the later part of the day. The excess attenuation is found to be around ~15 dB at 0.1% time of the year for a rain rate exceedance of ~55 mm/h. This high level of attenuation is found to be five times more than the annual average statistics.

Adji *et al* [65] determined the rain attenuation cummulative distribution for the Indonesian domestic satellite in Ku-band with an antenna elevation of ~85° based on 3 years propagation measurement in Surabaya, Indonesia. Their results show that the rain attenuation exceeding 1% of time is about ~2 dB from 1200 hrs LT to 2400 hrs LT which is ~1 dB more than the yearly average.

Radiometric measurments from a ~30 GHz site diversity experiment and that carried out with the OLYMPUS satellite at 12.5 GHz, 20 GHz and 30 GHz have been reported by Dintelmann *et al* [66]. The results indicate that if high availability (99.9% of time) of link is required, margins below 10 dB are sufficient with site diversity spacing of about 15 km. A comparison with the prediction based on ITU-R methods indicates that rain attenuation is overestimated for time percentage above 0.01%, while depolarization is underestimated significantly. Site diversity measurements around 8° elevation angles in Thailand were reported by Lekkla *et al* [67] based on 3-year radiometric study of rain attenuation at 12 GHz. Results from extensive experiments conducted to obtain attenuation information relevant for designing satellite communication in the 14/11 GHz band in south-east Asia (tropical moderate and wet climate zones) are also reported by them [67]. Radiometric measurements of rain and rain attenuation in New Zeland at Ku-band (11.6 GHz) were reported by Rodda and Williamson [68]. The measured rainfall rate profile was found to be well modelled by H-type ITU-R rain climate

(32 mm/h at 0.01% of time) as compared to K-type climate (42 mm/h at 0.01% of time). But the ITU-R attenuation model overestimates the attenuation statistics.

Abnormal events in radiometric measurements in Malaysia and path length reduction factor are reported by Yagesena *et al* [69]. Using ITU-R slant path procedure, the average of horizontal and vertical rain attenuation at ~0.01% probability level was found to be ~3.99 dB and 4.43 dB for ~45° and 90° elevation angles, respectively.

During radiometric data analysis, some abnormalities in the sky temperature were found. It usually increases during rain, but during abnormal events, high sky temperatures were recorded even when no rain was recorded at the ground by rain gauges. Ideally, the attenuation decreases with increasing the elevation angle, but it is not so when ITU-rain attenuation model is used. It is also found that the attenuation derived from radiometric measurements is higher than that derived from rainfall measurements. The difference could have been due to the path length reduction factor proposed by ITU-R. The rain attenuation calculated without the path length reduction factor (defined as the ratio between an equivalent path length over which the rain is assumed to be constant and the actual path length) follows the radiometrically derived attenuation, whereas the attenuation calculated using the redution factor is the opposite.

A joint African radiometric mesurement programme was set up to obtain data at frequencies above 10 GHz in tropical Africa [70] for slant path propagation. These experiments were conducted one in Doula, Cameroon (9.70°E, 4.05°N), one in Nairobi, Kenya (36.75°E, 1.30°S) and the third in Ile-Ife, Nigeria (4.34°E, 7.33°N) for 2 years starting from 1987. The results of the first and second year measurments from the above sites have been reported by McCarthy *et al* [71]. The average annual rain accumulation for the above three sites in Cameroon, Kenya and Nigeria were found to be ~4110 mm, 930 mm and 1400 mm, respectively. According to the ITU-R (formerly CCIR) rain cliamte zone designation, Cameroon comes under Q, Kenya under K and Nigeria between N and P zones. As far as the rainfall is concerned, the rain accumulations for the first and second year measurements (3213 mm and 2488 mm, respectively) were both found to be less than average annual accumulation for Cameroon. For Kenya, the second year measurment (770 mm) was less than the annual average, but the first year accumulation (1042 mm) exceeded the annual average value. For Nigerai, the heaviest rainfall of any month in the entire 2-year period occurred in August 1987 (297 mm). The total rainfall (1139 mm) for the second year was found to be less and for the first year to be more than average annual accumulation.

For Cameroon, the annual to worst months ratios for path attenuation were found to be smaller than those found in other temperate climate. Prediction of path attenuation by ITU-R generally underestimates the rediometrically derived cumulative distributions (CDs) of path attenuation. A possible cause may be the errors in the measurement of rainfall rate. Moreover, the ITU-R procedure may not match the rainfall rate characteristics. For Kenya, a relatively large ratio between worst months and annual rainfall rate CDs for a tropical climate is reflected in the derived path attenuation CDs. For Nigeria also a small ratio between the worst month and annual CDs is reflected in the derived path attenuation results. The ITU-R path attenuation prediction underestimated the derived attenuation significantly in the case of Nigeria too.

6.2. *Rain fades :*

Fade models are developed and improved using meteorological knowledge and data sets of concurrent rain and fade measurements. The major rain fade prediction models convert rainfall rate statistics into rain fade probabilities by using specific attenuation per unit distance together with the effective path length. Rain fade measurements at low elevation angle of 5.8° in Austin, Texas, are done by Vogel *et al* [72]. Rainfall statistics were taken by them at the satellite receiving site. At low elevation angle, scintillations of the beacon level (~5 dB at 0.01%) were observed even during rain fades. Therefore, attenuation values comprised both rain and scintillation effects. The year-to-year and seasonal variations of rain fade were found to be of the order of ~5 dB at 0.1% of time. The year-to-year variablity of cumulative rain attenuation at a given percentage of time was found to follow a log-normal process [73]. Monthly fade values were also found to follow log-normal distribution. The measured values were found to be much higher than those predicted by ITU-R method.

A new method for prediction of attenuation on satellite-earth links has been proposed by Watson and Hu [74] for systems operating with low fade margins. The physical rain structures on which the model is based include (i) a non-uniform vertical on-average profile of specific attenuation, (ii) the differing frequency dependencies of melting zone and rain components and (iii) contributions from widespread and showery rain. The predicted values at 40 GHz show good agreement with the measured values. At 20 GHz, the agreement is also quite good, although below 99.7% availability level, there is a tendency to overestimate. Similar tendency of overestimation is found at 12 GHz and 14 GHz also.

A detailed fade duration statistics has been reported by Safaai-Jazi *et al* [75] for rain attenuation on satellite-earth link at Ku-and Ka-bands. Contribution of rain to amplitude scintillation has also been examined using simulation measurements of rain dropsize distribution by a disdrometer and scintillation by satellite beacon receiver [76]. It has been shown that fluctuations of dropsize distribution contribute significantly to amplitude scintillation which is largest on horizontally polarized signals. A statistical relationship between rain attenuation and scintillation at 19 77 GHz that follows power-law was obtained by Matricciani *et al* [77].

Measurements of fade slope on 10–30 GHz earth-space were made by Nelson and Stutzman [78]. The results demonstrate that fade slope increases with frequency for a fixed occurrence level. Such results also suggest that as the attenuation level increases, the occurrence of large fade slope magnitude increases. If that is so, then one could probably infer that individual rain fades have higher fade slope magnitude with deeper fading. However, this depends on different parameters such as propagation path orientation, weather patterns, atmospheric conditions, *etc*.

The effect of fading on millimetrewave propagation and attenuation due to rain and sandstorms for arid climate of Saudi Arabia have been reported by Ali and Alhaider [79]. For most of the year Saudi Arabia gets very little rain and the rate of evaporation is higher than the rain rate. Therefore, rain attenuation is not the dominant factor for microwave propagation in arid climate of Saudi Arabia.

6.3. Depolarization vis-a-vis attenuation :

To cope up with the increasing demand for uplink and down link bands for communication satellites, the method, dual polarization frequency re-use (DPFR), has become the classical one. But, the system which uses this DPFR is subjected to depolarization mainly because of rain. Hendrix *et al* [80] have studied the relationship between rain attenuation and depolarization over a 7 km path. This path length was representative of the path length of a satellite-ground link which might encounter rain. Attenuation predictions, from dual polarization technique and the measured attenuation at ~11.6 GHz on a slant path using OTS satellite showed good agreement [81]. A theoretical relationship between rain attenuation and depolarization was obtained by Chu [82]. When the experimental values of cross-polarization discrimination were plotted against log attenuation, it was found that each rising and falling segment follows a straight line relationship. Studies on depolarization, cross-polarization, phase rotation, phase shift *etc.*, in relation to rain attenuation, have been conducted in the recent past by many others [83].

6.4. Attenuation along slant path :

Specific attenuation $\alpha(R)$ which is related to rain rate, R, through the eq. (1), is required for the estimation of total attenuation due to rain.

The CCIR method of calculation of total attenuation along the slant path is given by [7]

$$A_R = \alpha(R) L_e, \tag{12}$$

where A_R is the attenuation exceeded for P% of time, $\alpha(R)$ the specific attenuation and L_e the effective path length given by

$$L_e = r_p L_s, \tag{13}$$

where r_p is the reduction factor and is given by

$$r_p = \frac{90}{90 + C_p L_G} \tag{14}$$

and

$$L_s = (H_t - H_o)/\sin\theta, \tag{15}$$

Here, H_t is the 0°C isotherm height and H_0 is the station height above mean sea level and θ is the elevation angle. The values of C_p as given in the CCIR [7], are 9, 4, 0.5 and 0, respectively, for rain occurring for 0.001%, 0.01%, 0.1% and 1% of time. The parameter L_G is the horizontal projection of the slant path.

Based on the concept of moving rain cells a new model has been developed by Hansson [84] for the prediction of attenuation from rain rate statistics over slant path. Calla *et al* [85] have provided path reduction factor for estimating slant path attenuation over India. Expressions are derived for attenuation estimation by using a rain cell model suggested by Costa *et al* [86], considering converging links in Sao Paulo, Brazil. These expressions are adjusted to the experimental data to estimate the different parameters used in the model. It was observed that the model was not capable of reproducing acceptably the measured rainfall rate. But since the attenuations are integrated effects of the rainfall rate according to the derived expression, a reasonable agreement was found between measured and estimated attenuations.

Differential rain attenuation is recognized as one of the main problems relating to propagation effects on interference between two adjacent earth-space paths operating at the same frequency. A model for the prediction of differential rain attenuation over such paths was proposed by Kanellopoulos and Kossidas [87]. The model is based on convective rain cell structure of rainfall medium and the assumption that point rainfall statistics follow log-normal distribution.

In India a number of experimental studies have been carried out by different groups. Raina [88] has shown that the attenuation values obtained from radiometer observation at frequencies 11 GHz and 18 GHz over Delhi, agree with CCIR values. Similarly Tewari *et al* [89] at Dehradun and Sen *et al* [90] at Calcutta have shown that the rain attenuation at ~11 GHz and 17 GHz over Debradun and that at ~11 GHz over Calcutta have good agreements with the CCIR prediction.

Sarkar *et al* [91] have studied cm and mm-wave attenuation due to rainfall over a tropical station, Delhi. A rapid response rain gauge was used for the measurements of rain rates for which the results on attenuation of radio wave (cm and mm-wave) were derived for frequencies between 10 GHz and 400 GHz. Since the dropsize distributions as well as the rainfall rates vary from location to location and as the rain drops have non-spherical nature of shape, the atenuation prediction becomes complex. An observational study over LOS microwave link at ~11 GHz has been carried out by Timothy *et al* [3] at Guwahati to understand the rain attenuation characteristics. They found that the rain attenuation values over this LOS link of path length 3.2 km are higher than those predicted from CCIR models. But at the same time, these values are found to follow very closely the values obtained from the log-normal dropsize distribution model. Thus, where the rain attenuation values over Delhi [88], Calcutta [90] and Dehradun [89] were found to follow the CCIR prediction, the rain attenuation values at Guwahati were found to be higher than CCIR values.

Though the attenuation has got maximum correlation with the rainfall rate, it has been observed by Timothy *et al* [3] that there are cases when large attenuations are produced by very low rainfall rate. This large attenuation due to low rain rate cannot be explained in terms of low rainfall rate alone. Again, it was observed that there was practically no attenuation for the months other than April, May and June even for the rainfall rates that produced attenuation during April, May and June. One probable cause for this may be the rain dropsize distribution which varies from location to location and rain type to rain type. In the drop diameter range of 3–4 mm, the attenuation is found to increase by ~1.4 dB per 1 mm increase in diameter for the diameter range ~4–5 mm. Rucker [92] from an analysis of attenuation measurements at 12.5 GHz, 20 GHz and 30 GHz made by OLYMPUS propagation experiments with regard to rate of change of attenuation (fade slope), found that the prominent fade slopes occur when the attenuation range is high.

Based on the observed rain rates and rain height in relation to 0°C isotherm heights, the results on attenuation of radiowave due to rain for 0.1% and 0.001% of the time over Calcutta have been derived by Mondal *et al* [93] using the CCIR [7] method. The attenuation values over Calcutta for ~80 mm/h which exceeds for 0.1% of time is found to be 80 dB at ~30 GHz. It is seen that the measured rain rate ~120 mm/h exceeds for 0.01% of time over Calcutta and the attenuation value at 0.01% of time is ~100 dB. The results on attenuation for rain rate ~185 mm/h, over Calcutta have also been obtained. Such rain rate exceeds for ~0.001% of time. The attenuation value at ~30 GHz is found to be ~132 dB.

Studies on the measurements of atmospheric water vapour and rain attenuation have recently been made by Sarkar *et al* [94]. Large area of low rain rates and number of smaller regions with high rain rates are the characteristics of precipitation. These characteristics make the spatial distribution of rain difficult to describe. The rain attenuation can be predicted more accurately if the rain rate characteristics over the entire path of propagation, *i.e.*, from transmitter to receiver, are known. An exponential shaped effective profile for rain rate and the concept of rate of decay of rain path profile as proposed by Stutzman and Dishman [95] was adopted by Mondal *et al* [93] for the estimation of rain attenuation. The theoretically estimated attenuations were compared with the observed values, as well as with values obtained using CCIR method [eq. (12)]. The Stutzman and Dishman model was found to agree well with the observed values as shown in Figure 11 for a γ-value of 0.033 (γ is a parameter that controls the decay rate of rain path profile) over tropical Indian station having satellite link at an elevation angle of ~56°.

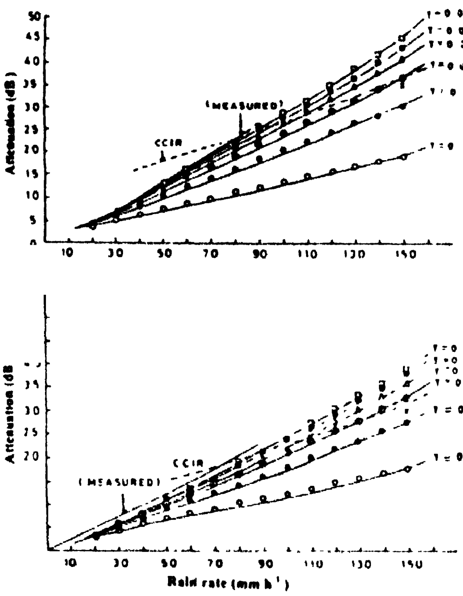

Figure 11. The variation of attenuation with rain rates for different values of γ at 13.4 GHz with θ = 56°; and for (a) H_i = 5.5 km and (b) H_i = 4.5 km

7. Conclusions

From all these studies it is observed that rain has tremendous effect on radiowave operating in microwave and millimetrewave frequency bands. Since India is a tropical country and has widely varied climatic zones and varieties of rain structure, there is a need to go for a rigorous analysis of rain pattern and attenuation of microwave and millimetrewave frequency bands over different path lengths.

The works done by Sarkar *et al* [37] and Mondal *et al* [38] on 0°C isotherm height, as reported, cover only the stations Calcutta, Trivandrum, Bombay, Gauhati, Lucknow and Delhi. Therefore, work on 0°C isotherm height can be extended for other stations. Some work on 0°C isotherm height over various stations are already in progress. Network of 0°C isotherm height will provide us an opportunity to estimate rain attenuation over different locations in India. The system designer may go for the improvement of their systems for better communication with these results. Again, validity of Stutzman and Dishman model [95] as examined by Mondal *et al* [93], for a particular value of a parameter that controls the decay rate of rain path profile over a tropical Indian station, has been extended to other stations like Shillong, Calcutta, *etc.* and already reported [96]. Whether the same value of that particular parameter (γ) of the model holds good or not for many more Indian stations, are yet to be seen.

The studies on dropsize distribution as reported by Jassal *et al* [44] and Verma and Jha [48] are mainly confined to the station Dehradun in India, while that reported by Timothy *et al* [49] pertains to the Indian hilly station Gauhati. India being a vast country, these studies can be extended to other stations spreading over different climatic regions of the land.

Determination of cumulative distribution of rainfall rate from data collected at different station is very much necessary for designing communication links in microwave and millimetrewave bands throughout the country. It is suggested that measurements of equivalent rain path from simultaneous measurements of rain rate and amplitude variation may be made over other stations. Correlation of rainfall rates between two locations as a function of separation distance, seasons and integration may also be found. Study of the effects of environmental parameters, like vegetation, forest, building, factory releases including gas and smokes on rain rate and fluctuation in microwave and millimetrewave attenuation may be undertaken. The variation of rain drops between coastal and non-coastal region in terms of chemical compositions such as sodium chloride (NaCl) and potassium chloride (KCl) that may affect the attenuation, may be an important topic for future study. Similarly, the acid rain, particularly, in industrial area attenuates the microwave and millimetrewave differently. Therefore, this type of rain should also be given due importance for rain related attenuation studies in future. Estimation of rain attenuation for different stations may be made. The effect of attenuation due to change in canting angle may also be investigated. The zenith water vapour attenuation on the basis of water-vapour contours atlas over Indian subcontiment may be prepared. The change in cloud-top temperature with rain may also be investigated.

Efforts are to be made in future to gather as much as measured data on field strength at frequencies higher than 10 GHz by using communication links which are in operation by various agencies located in different geographical regions. Once these exercises are done, such operations will provide opportunities to compare the estimated results with the observed results. On the basis of comparative results, the methods such as ITU-R, Stutzman and Dishman methods, *etc.* may be modified for using in the Indian conditions. Secondly, rain dropsize distributions results are not available in many places in India. Theoretical prediction of attenuation depends considerably on the rain dropsize distribution, which varies within rain events, from one event to another and from place to place. The smaller rain drops contribute more to attenuation in higher frequencies. Reliable dropsize model has not yet been developed due to non-availability of sufficient data on dropsize distribution over different climatic regions in India. In future, it is to be planned to have measurements on rain dropsize distribution, particularly, over such areas where monitoring of microwave link is made along with the rain rate measurements by using rapid response rain gauges. The characterization of rain is important for estimation performance of communication links and radar propagation in microwave and millimetrewave bands and such exercises on rain characteristics by using weather radar are to be made. Some new weather radars at 3 cm (10 GHz) have been installed very recently over many stations by the Indian Meteorological Department. Such radars may be used, particularly, during the rainy period/season to obtain the details of the characteristics of rain including its microstructure in relation to the horizontal extension, vertical extension, effects of elevation, orientation, rain dropsize distribution, rain cell separation, evolution of rain, cloud characteristics, *etc.* Efforts are also to be made to obtain the results on attenuation of radiowave by using 10 GHz (3 cm) weather radar from radar echo measurements. Computer-aided contour plottings of rain intensity and rain attenuation may also be possible if enough data are generated.

Acknowledgments

The authors are thankful to various research workers whose contributions reported in different journals, proceedings and publications, have been utilized for the preparation of this paper.

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